FINAL TECHNICAL REPORT
April 9, 1994

Ultra-High Aggregate Bandwidth Two-Dimensional Multiple-Wavelength Diode Laser Arrays

Grant Number N00014-93-1-0558
R&T Project: 4145my2---01

Principal Investigator:
Prof. Connie Chang-Hasnain
Ginzton Lab and Electrical Engineering Department
Stanford University
Stanford, CA 94305-4085
Tel (415)723-0111; Fax (415)725-7509
e-mail: cch@sierra.stanford.edu

Scientific Officer:
Dr. Max Yolder
ONR-3140, Room 607
Office of the Chief of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660

Approved for public release; distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
April 9, 1994

3. REPORT TYPE AND DATES COVERED
Final - April 10, 1993 to April 9, 1994

4. TITLE AND SUBTITLE
Ultrahigh Aggregate Bandwidth Two-Dimensional Multiple-Wavelength Diode Laser Arrays

5. FUNDING NUMBERS
N00014-93-1-0558

6. AUTHOR(S)
Connie Chang-Hasnain

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ginzton Lab
Stanford University
Stanford, CA 94305-4085

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Max Yolder
ONR-3140, Room 607
Office of the Chief of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Two-dimensional (2D) multi-wavelength vertical cavity surface emitting laser (VCSEL) arrays is promising for ultrahigh aggregate capacity optical networks. A 2D VCSEL array emitting 140 distinct wavelengths was reported by implementing a spatially graded layer in the VCSEL structure, which in turn creates a wavelength spread. In this program, we concentrated on novel epitaxial growth techniques to make reproducible and repeatable multi-wavelength VCSEL arrays. Our approach to fabricate the spatially graded layer involves creating a nonuniform substrate surface temperature across the wafer during the growth of the cavity spacer region using the fact that the molecular beam epitaxy (MBE) growth of GaAs is highly sensitive to the substrate temperature. We successfully demonstrated a periodically chirped vertical cavity with 8 nm wavelength shift on a substrate with a 3 mm period pattern-induced temperature gradient. We also built a reflectivity measurement apparatus that is capable of mapping a 2" wafer for diagnosing our wafers. In this final 12-month report, we present our experimental results and a discussion on future directions.

14. SUBJECT TERMS
MBE, patterned substrate, VCSEL

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	UL

Table of Contents

A. INTRODUCTION

The goal of this project was to explored novel epitaxial growth techniques that can result in the growth of a GaAlAs layer with a controlled and periodic thickness gradient. Such periodically graded layer is the key to the fabrication of two-dimensional (2D) multi-wavelength vertical cavity surface emitting laser (VCSEL) arrays [1] with repeatable and reproducible wavelength spans. Multi-wavelength VCSEL array is promising for ultrahigh aggregate capacity optical communications and interconnects with the use of wavelength-division-multiplexing (WDM). Specifically, 2D multi-wavelength VCSEL array can play a major role as a highly cost-effective optical source for achieving ultrahigh aggregate bandwidth (Tera Hertz) optical communications and interconnects using wavelength division multiplexing (WDM). For example, such ultrahigh bandwidth communications will be particularly promising for interconnecting all computers and instruments within aircraft, battleships, aircraft carriers, and any moving vehicles. Major advantages include cost-effectiveness (as compared with other diode lasers, e.g.. DFB lasers), light weight, and free of interferences (as compared with electronics).

Our approach to fabricate the spatially graded layer involves creating a tapered substrate surface temperature across the wafer during the growth of the cavity spacer region. Using the fact that, during an molecular beam epitaxy (MBE) crystal growth, the GaAs growth rate is highly sensitive to the substrate temperature above 650°C [2-3]. We first began with a calculation of the surface temperature distribution for a wafer with periodic heating elements on its bottom side. This calculation then guided us towards the optimum growth conditions. Vertical cavity structure was grown on substrates with various etching and mounting preparations, which are used to create the periodic heating conditions on the back of the substrate. The Fabry-Perot (FP) wavelength of the vertical cavity structure is thereafter measured and mapped using a home-built automated reflectivity spectra measurement apparatus.

Among various wafer preparations, we found that it is most effective with the use a patterned backing substrate bonded to the growth substrate. We demonstrated an 8 nm shift in the FP wavelength with a 3 mm period pattern. This is to our knowledge the first such demonstration. We are continuing to experiment with growth parameters to produce larger wavelength shifts over smaller periods. In this report, we present our results, and a discussion of the impact of this research and future applications.

B. SUMMARY OF PRINCIPAL ACCOMPLISHMENTS

1. Modeling

1.1 Cavity Design

The test structure we grew typically consists of a passive GaAs cavity with Bragg reflectors (10.5 pairs on the substrate side and 8 pairs on the top) consisting of quarter-wave AlAs/GaAs layers designed at 950 nm. Since we are interested to establish a growth method, the simplified passive vertical cavity is used rather than the more time-consuming VCSEL structure. As mentioned before, the graded layer is to be used to control the lasing wavelength of a VCSEL without any compromise in the reflectivities of the distributed Bragg reflectors (DBR). Thus, it is highly important to be able to only grow the cavity layer with a gradient while keeping the rest of the vertical cavity structure uniform. This can be done by realizing that the GaAs growth rate is a strongly decreasing function of temperature above substrate temperatures of 640 C [2]. Thus, both DBRs should be grown at a substrate temperature lower than 640 C (~600 C) and the cavity is grown at higher temperature (~ 700 C).

Figure 1 shows the calculated reflectance spectra of a passive Fabry-Perot (FP) cavity with its central GaAs layer thicknesses being 240 nm, which is the standard design of one-wavelength thick, and 300 nm, which is 25% thicker than the standard. This calculation gives a realistic estimate of the FP mode shift we can achieve across the wafer. For a 25% growth rate variation we can expect a lasing wavelength difference of over 50 nm. The question that remains is how sharp of a temperature profile we can expect to achieve, which will determine the minimum spacing of the devices. In the next section we estimate the temperature profile along the wafer surface given a temperature gradient on the back side.

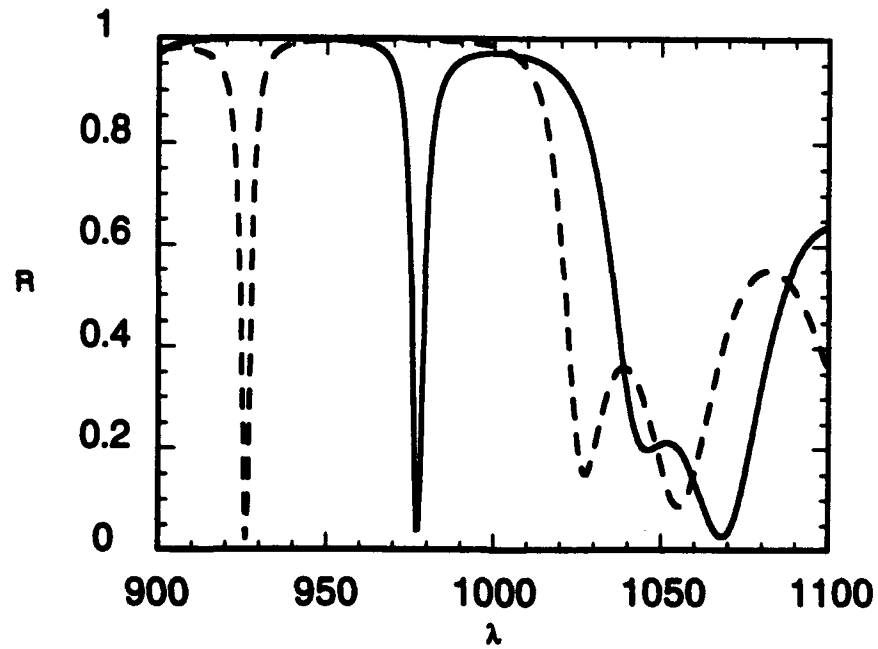

Fig. 1 The calculated reflectivity spectrum of a passive Fabry-Perot cavity with cavity thicknesses of 240 nm (dashed line) and 300 nm (solid line).

1.2 Estimate of Surface Temperature

We use the following simple model to estimate the surface temperature profile. Given a temperature profile on the back side of the wafer one can calculate the temperature profile at the substrate surface by solving the steady state heat equation

$$\Delta T(x,y,z) = 0$$

where Δ is the Laplacian operator with appropriate boundary conditions. It is the surface temperature that will determine the GaAs growth rate. As a first order approximation in one dimension, we consider an infinitely thick wafer with fixed temperature boundary conditions on the back side given by

$$T(x,0) = T_2 \quad \text{for } |x|<L/2$$

$$T(x,0) = T_1 \quad \text{for } |x|>L/2$$

This problem can be solved analytically using conformal mapping techniques [4], and the solution is

$$T(x,y) = T_1 + (\delta T/\pi)\,\mathrm{Arctan}\{Ly/[x^2 + y^2 - (L/2)^2]\}$$

The result of this calculation is shown in Figure 2. As we move away from the x axis, i.e. increasing y, the temperature profile smears out. For y =L/2, the maximum difference in temperature along x is only 40 % of the difference, δT, on the back side. We can expect to see the effects of spatial temperature variations on the surface for features of the same order or larger than the substrate thickness.

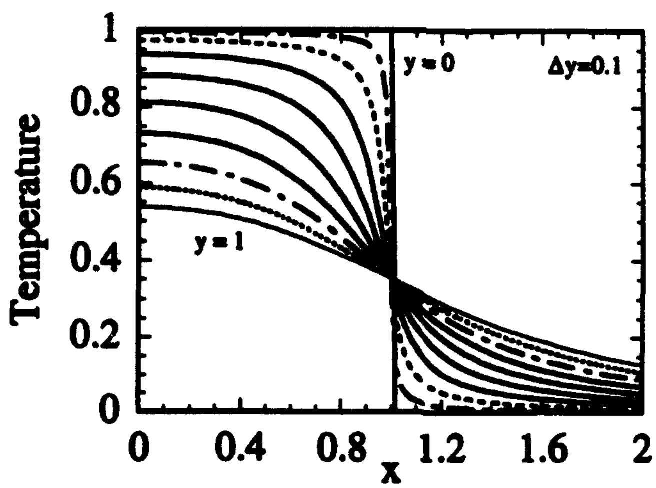

Fig. 2. Calculated temperature profile along x for various distances from the y axis. The temperature axis is scaled by dT and offset by T1 and the x and y values are in units of L/2.

2. Experimental Progress

2.1 Low-Threshold Edge Emitting Lasers

Before attempting to grow VCSEL laser structures, it is necessary to evaluate the quality of the material grown in the MBE system. We use the threshold current density of 100 μm wide broad area edge emitting lasers as a test of the material quality. We have grown and fabricated a InGaAs strained quantum well graded-index separate-confinement-heterostructure (GRIN-SCH) laser structure [5] with very low threshold current densities of ~200 A/cm^2. This is very comparable to the best reported values for short cavity lengths (~500 μm).

2.2 Wafer-Scale Reflectivity Spectra Measurement System

We completed the construction of a wafer-scale reflectivity spectra measurement apparatus (see Fig. 3) for the characterization of the passive cavity test structures. The reflectometry measurement system can measure the Fabry Perot wavelengths across a 2" wafer. The spatial resolution of this system is determined to be as small as 100 μm. This system can automatically scan across the wafer, store the reflectance spectrum, and find the cavity mode at each point for an arbitrary grid size.

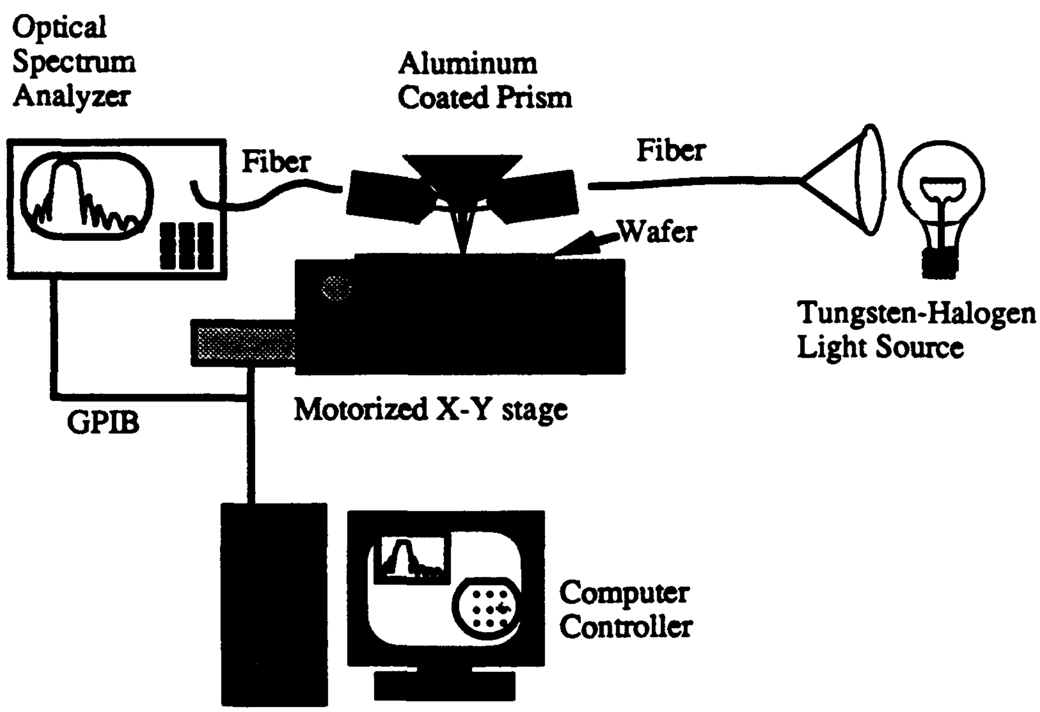

Fig. 3. Schematic of our reflectivity measurement apparatus

2.3 Patterned-Substrate MBE Growth of VCSEL Cavity

We grew 15 wafers of the test structure described earlier with various substrate backings and substrate temperatures to establish the proper growth conditions. The substrate heating mechanism of the particular MBE system we are using is done by radiative heating from a filament. This is different form what is used in ref. 3. Hence, the methods we are investigating to create the temperature-dependent growth patterns are substantially different. Fig. 4 shows the

various growth conditions we used including (a) substrate backed with a Si wafer having etched through holes, (b) substrate backed with a GaAs wafer having etched through holes, and (c) substrate backed with a GaAs substrate with etched grooves. The pattern sizes we have experimented range from 100 μm to 3 mm in size and the etched grooves are typically 200 μm deep. Two GaAs wafer thicknesses, 500 μm and 200 μm, were also experimented.

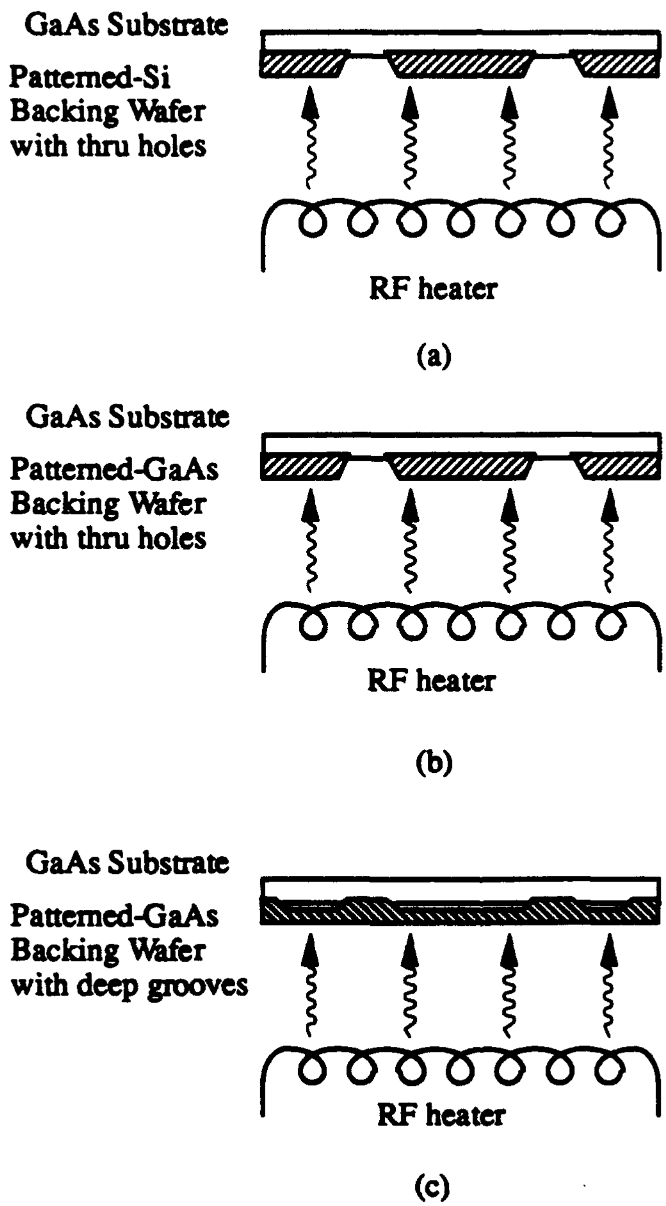

Fig. 4 Schematic of the various growth conditions we are investigating to induce a periodic growth variation on the wafer, including (a) substrate backed with a Si wafer having etched through holes, (b) substrate backed with a Ga wafer having etched through holes, and (c) substrate backed with a GaAs substrate with etched grooves. The substrate heating mechanism of this particular system is done by radiative heating from a filament.

All our earlier attempts were in vain and no pattern-induced FP shift was observed. Various diagnostic measurements were done, which led us to conclude that method (c) would be most promising provided a good thermal contact is attained between the backing wafer and the growth wafer. We then use In as a solder to bond the backing and growth wafers, as shown in Fig. 5. Indeed a pattern-induced period FP shift was achieved. Fig. 6 shows the FP wavelength as a function of position for a wafer with a backing with 3 mm period patterns. A significant shift of 8 nm having a 3 mm period is obtained. A 2D contour plot for the Fabry-Perot mode wavelength is shown in Fig. 7. The periodic wavelength shift is more clearly seen here. The nonuniformity is, however, due to the difficulty in making good thermal contact with the indium bond. Figure 8 shows the measured reflectivity spectra at various positions. We see that although the FP cavity mode shifts significantly, the stop band of the reflectance stays nearly constant indicating that the reflectivities of the DBRs are not effected.

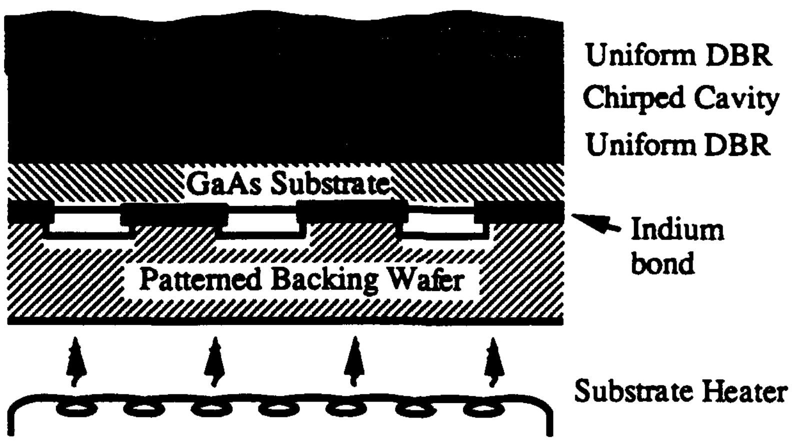

Fig. 5 Schematic of the growth using In-bonded patterned backing substrate

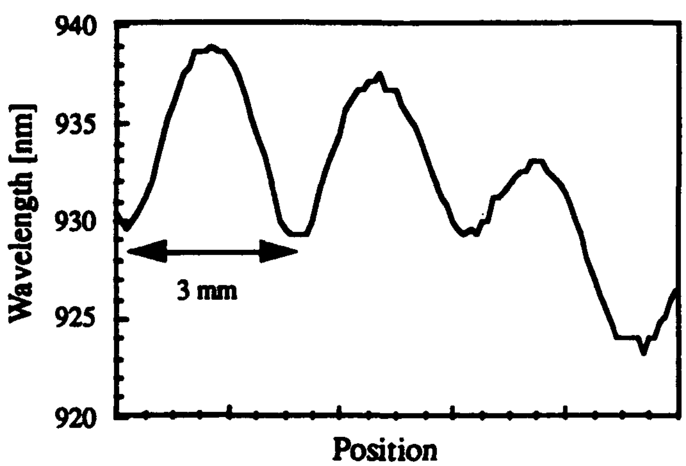

Fig. 6 Cavity mode wavelength vs position for a periodic 3 mm backside pattern.

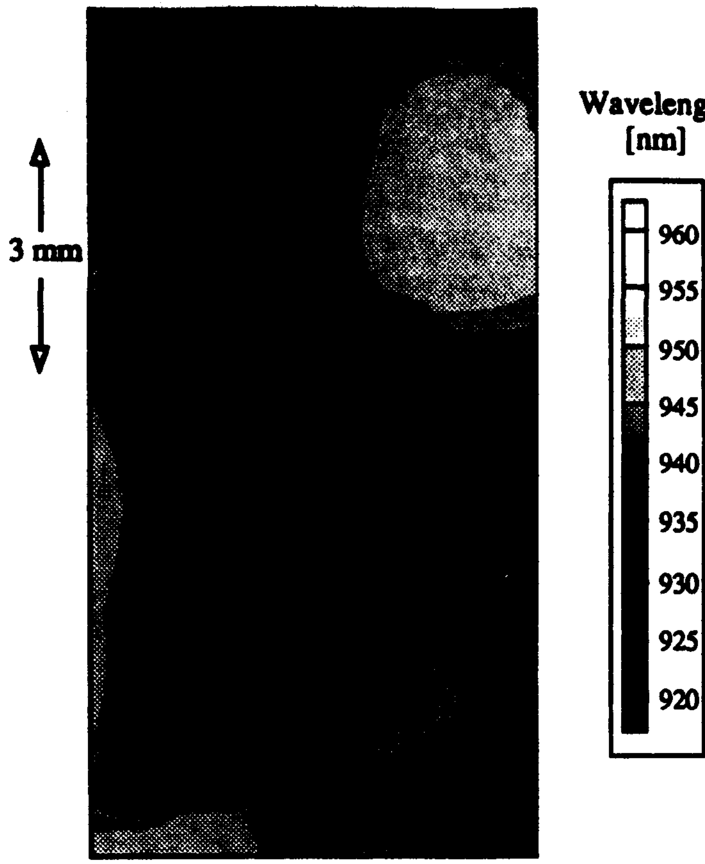

Fig. 7 2D contour plot of the Fabry-Perot mode on the patterned substrate.

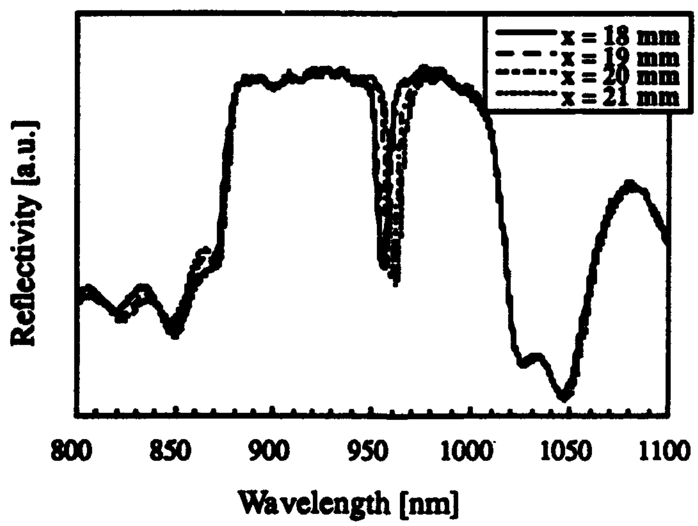

Fig. 8 Reflectivity spectra at four different positions on wafer.

C. IMPACT OF RESEARCH

We have demonstrated a novel growth technique which allows us to fabricate a controlled periodic thickness gradient. The results will be useful for fabricating multi-wavelength VCSEL arrays and optical tapered waveguides. The 2D multi-wavelength VCSEL array can play a major role as highly cost-effective WDM transmitters for ultrahigh bandwidth optical communications and interconnects. A particular promising application would be interconnecting instruments and computers within aircraft, destroyers, and other vehicles. Commercial applications include computer interconnects and multi-media fiber communications. Tapered waveguides, on the other hand, are essential for fiber coupling with in-plane devices to improve the packaging costs. The technique of growing cavities above the gallium desorption temperature and spatially mapping the cavity mode can also be used as a tool to study substrate temperature uniformity, since the measurement is sensitive to cavity thickness variations of less than 1%.

D. FUTURE DIRECTIONS

We will be experimenting with the growth conditions and the parameters of the patterns of the patterned substrate to optimize the growth of the graded layer. We will fabricate multi-wavelength VCSELs with the periodically graded layer in the cavity. We will be setting up VCSEL array packaging and fiber coupling facilities. Finally, we hope to demonstrate WDM optical interconnects using the multi-wavelength VCSEL arrays.

E. PUBLICATIONS

1. L. Eng, K. Toh, C.J. Chang-Hasnain, K. Bacher and J.S. Harris, "Periodically Induced Mode Shift in Vertical Cavity Fabry Perot Etalons Grown by Molecular Beam Epitaxy," to be presented at the IEEE LEOS Summer Topical Meeting on Optoelectronic Materials Growth and Processing, Lake Tahoe, NV, July, 1994.
1. L. Eng, K. Toh, C.J. Chang-Hasnain, K. Bacher and J.S. Harris, "Periodically Induced Mode Shift in Vertical Cavity Fabry Perot Etalons Grown by Molecular Beam Epitaxy," to be submitted to the Photonics Tech. Lett.

F. REFERENCES

1. C.J. Chang-Hasnain, J.P. Harbison, C.E. Zah, M.W. Maeda, L.T. Florez, N.G. Stoffel, and T.P. Lee, IEEE J. Quantum Electron, 27, 6, pp.1368-1376, June 1991.
2. R. Fischer, J. Klem, T.J. Drummond, R.E Thorne, W. Kopp, H. Morkoc, and A.Y. Cho, J. Appl. Phys., 54,2508 (1983).
3. D.E. Bossi, W.D. Goodhue, M.C. Finn, K. Rauschenbach, J.W. Bates, and R.H. Rediker, Appl. Phys. Lett., 56, 1092 (1990)

4. R.V. Churchill, J. W. Brown, and R.F. Verhey, *Complex Variables and Applications*, 3rd edition, McGraw Hill, 1974
5. L.E. Eng, T.R. Chen, S. Sanders, Y.H. Zhuang, B. Zhao, H. Morkoc, and A. Yariv, Appl. Phys. Lett., 55, 1378 (1989).